An Investigation of non-Bragg Scattering from the Sea Surface

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LONG-TERM GOALS

The long-range objective of this work is to investigate non-Bragg sea surface scattering at intermediate angles of incidence. We seek to define the characteristics and statistical properties of these scatterers and to establish a link between radar observations and the underlying physical processes.

OBJECTIVES

Our objective is to investigate scattering from the sea surface that seemingly cannot be explained using composite surface models based on Bragg scattering theory. Models based on Bragg scattering adequately predict most backscatter observations, but several phenomena are not well predicted using this type of approach, suggesting the models exclude some relevant physical processes. This research examines scattering events that are apparently inconsistent with composite surface theory, and seeks to identify prospective mechanisms and to develop predictive models for these non-Bragg scatterers.

APPROACH

Our approach is to analyze data from the SAXON-FPN experiment conducted in 1990/1991 (described in detail by Plant and Alpers, 1994) to define the physical and statistical characteristics of non-Bragg sea surface scattering. This data set includes simultaneously acquired horizontally (HH) and vertically (VV) polarized radar cross-section observations at several frequencies, and detailed environmental measurements. The ratio of HH-to-VV cross sections is commonly used to separate Bragg and non-Bragg scattering. Since Bragg scattering predicts that on average VV cross sections should be larger than HH at moderate incidence angles, events for which the HH cross sections exceed the VV are often designated as non-Bragg scattering. We have investigated the ratio of HH-to-VV, previously used as a criterion for designating non-Bragg scattering events, by comparing the data with simulations based on composite surface theory, and through statistical analysis of the observations. We have found that the polarization ratio does not serve as a useful metric for identifying non-Bragg scattering. To explain events where HH cross-section exceeds VV, we have investigated physical mechanisms including bound waves and sea spray. In addition, we have analyzed the characteristics of extreme

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14. ABSTRACT
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15. SUBJECT TERMS

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backscattering events for both polarizations using both statistically- and physically-based methods. These investigations are described in the following sections.

WORK COMPLETED

Our earlier work on this project found that the frequency of events for which HH>VV depended strongly on the averaging time. We also found that given the effects of tilting, modulation and signal fading, the condition HH>VV is not inconsistent with Bragg scattering theory, particularly when short averaging times are considered. Monte-Carlo simulations, probabilistic, and composite surface theoretical models, all supported our conclusion that detecting HH cross sections that are larger than VV cross sections are not by themselves proof of non-Bragg scattering. Only if the probability of such events in the data is significantly higher than indicated by a Bragg scattering simulation can we possibly infer from polarization data that scattering processes other than Bragg have been observed; if the Bragg scatterers are tilted, even this may not suffice. To resolve this issue we pursued two distinct, but related lines of inquiry: in the first, we investigated specific physical mechanisms, such as bound waves and sea spray, to determine whether or not they could account for the backscattering observed for HH and VV polarization. In the second, we apply a class of non-Gaussian statistical distribution functions known as alpha-stable (α-s) models to model and predict backscattering from the sea surface for both polarizations.

RESULTS

1. Investigation of Bound Waves and Sea Spray. Last year we showed that finding HH cross sections, σ_o(HH), that were larger than VV was not proof of non-Bragg scattering if the integration time is short. Bragg scattering theory applied to freely propagating wind waves predicts nearly identical probabilities of detecting $\sigma_o(HH) > \sigma_o(VV)$ for the mid-range of incidence angle. Our further work has shown that the addition of Bragg scattering from bound waves, i.e., tilted waves generated by longer waves and moving with them, is insufficient to predict observed values of this quantity at high incidence angles. Our work also shows that mean values of σ_o(HH) are under predicted at high incidence angles even with the addition of bound wave effects, although σ_o(VV) is predicted accurately. Figures 1a and 1b illustrate this result at wind speeds of 7 and 13 m/s. Figures 1c and 1d show that the addition of a small additional component of cross section, $\Delta\sigma_o$, that is independent of incidence angle and polarization, but increases with wind speed, brings simulations into agreement with observations. Note that the addition of $\Delta\sigma_o$ has almost no effect on σ_o(VV).

We have suggested that the cause of this additional, non-Bragg scattering may be spray above the air/sea interface. If the spray droplets are spherical, then backscatter from them is independent of incidence angle. If concentrations of spray droplets are not too high, then the droplets attenuate the microwave beam very little as it passes through them and their backscatter is independent of incident angle. We have used a spray drop size distribution measured recently in a wind wave tank (Chris Fairall, private communication) to model the additional backscattering produced by spray. The results are shown in Figure 2.

Clearly, the resulting $\Delta\sigma_o$ is very close to that necessary to bring simulated and observed σ_o(HH) values into agreement. Droplet concentrations that yield this result are near 4 drops/cm^3, which is sufficiently low to preclude significant attenuation. The problem with this explanation of the non-Bragg backscatter is that we have had to use a wind speed dependence of U^1 for the spray droplet concentrations while the tank observations increase as U^5. Until this discrepancy is resolved, this explanation of the large observed values of σ_o(HH) at high incidence angles cannot be considered to be fully acceptable. These results have recently been published in Waves in Random Media (Plant, 2003b).

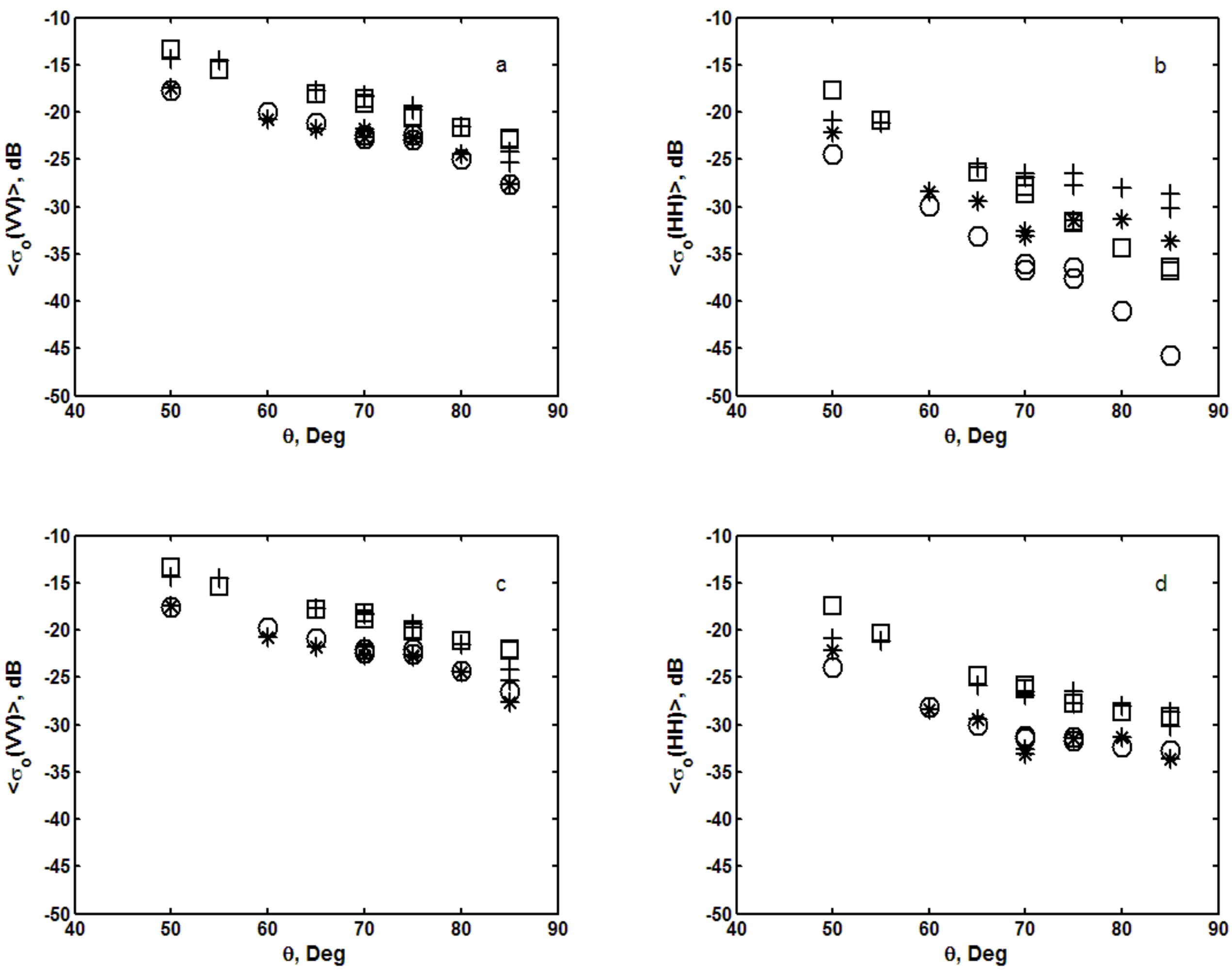

Figure 1. Measured and simulated mean cross sections versus incidence angle, θ. Wind speed 6 to 8 m/s: asterisks = measured, circles = simulated; wind speed 12 to 14 m/s: pluses = measured, squares = simulated. a) σ_o(VV) versus θ; b) σ_o(HH) versus θ; c) σ_o(VV) versus θ with $10^{\Delta\sigma o/10}$ added to the simulated σ_o(VV); d) σ_o(HH) versus θ with $10^{\Delta\sigma o/10}$ added to the simulated σ_o(HH). All simulations include Bragg scattering from both free and bound waves. $\Delta\sigma_o$ = -33 dB at a wind speed of 7 m/s and -30 dB at 13 m/s.

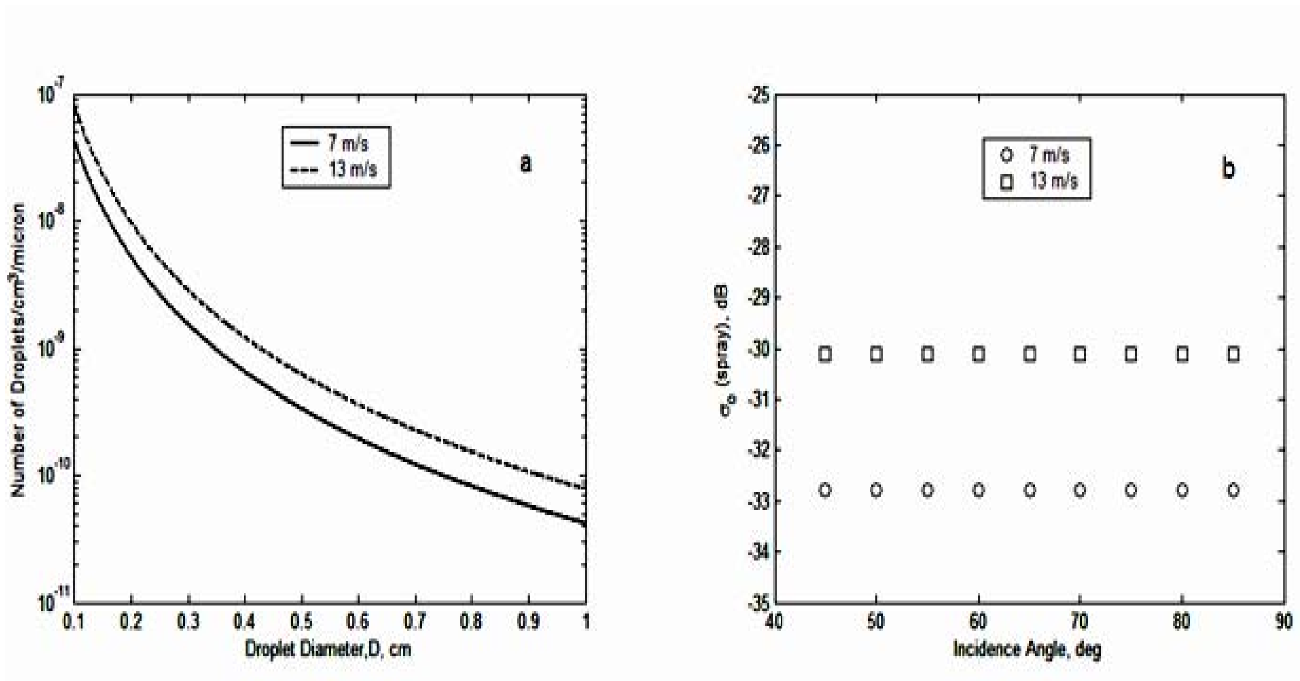

Figure 2. a) Assumed distribution of spray droplets, and b) their resulting normalized radar cross section versus incidence angle at two different wind speeds.

2. Application of Alpha-Stable Modeling of Sea Surface Scattering. At high spatial and temporal resolution, models for the probability density function (pdf) of radar backscattering from the sea surface fail to adequately predict the occurrence of impulsive events possessing anomalously high backscattered power for both HH and VV. These significant but occasional events elevate the tails of the distribution, making them inconsistent with the assumption of Gaussianity, prompting the use of a variety of non-Gaussian distributions, such as the Rayleigh, lognormal, K, and Weibull distributions, none of which accurately predict the behavior observed in the tails of the distribution. The alpha-stable (α-s) class of distribution functions is ideally suited for modeling non-Gaussian, impulsive phenomena and we have used α-s models to predict oceanic backscattering in two different investigations. In the first, we use α-s models to directly model observations of oceanic backscattering, and compare our predictions with the other non-Gaussian models. In the second, we extend an approach suggested by Guerin [2002], and use an α-s model to characterize the wind-roughened sea surface, from which the corresponding surface scattering is obtained via the Kirchhoff approximation (KA) or the small slope approximation (SSA) [Voronovich, 1994]. We compare these results with observations from the SAXON-FPN experiment.

In Figure 3 we fit an α-s model to backscatter measurements obtained at Ka-band (35 GHz) with a 45^{o} angle of incidence. The two upper panels depict time series of simultaneous, collocated HH- (left panel) and VV-polarized (right panel) backscattered power measurements at 200 Hz. The lower two panels use four different models (the s-α-s, Gaussian, exponential and Weibull models) to model the pdf of the backscattered power associated with the sequences shown in the upper panels.

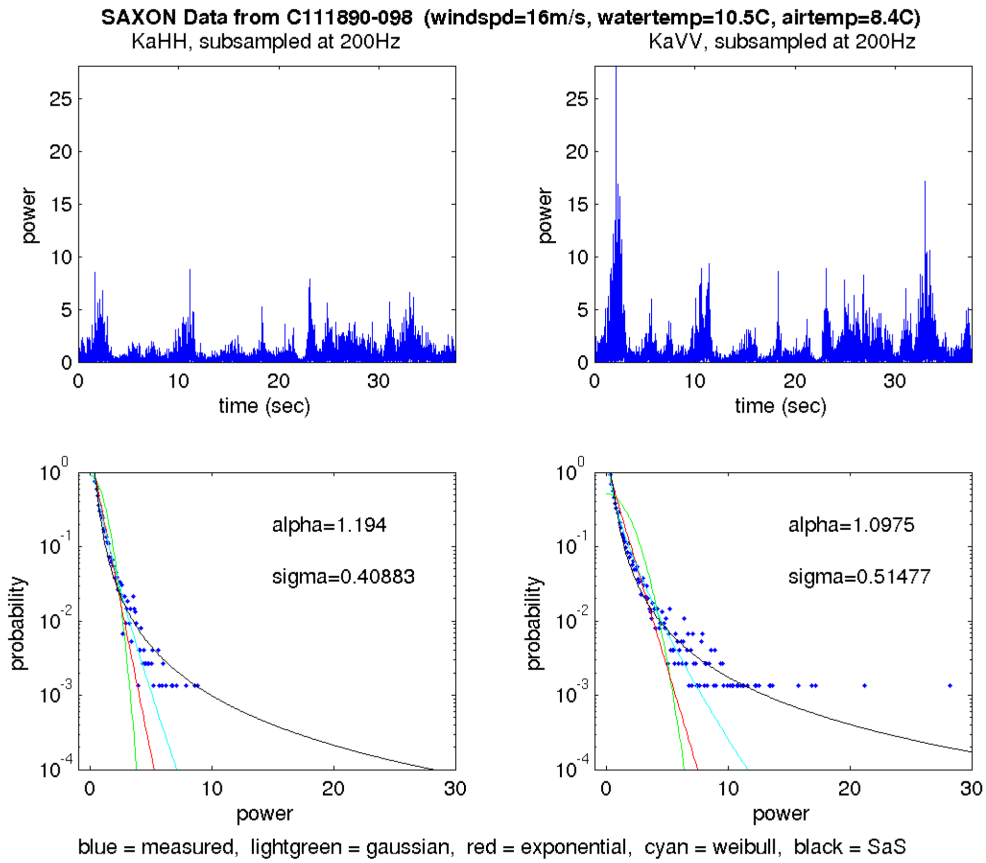

Figure 3. Pdf for Ka-band backscatter measurements (obtained at 2 kHz, downsampled to 200 Hz), compared with Gaussian, exponential, Weibull and α-s models. Experimental conditions include a slightly unstable atmospheric boundary layer and moderate (16 ms^{-1}) winds; wind and look directions are aligned.

The parameter α characterizes the 'spikiness' of the data (as α approaches 2, the distribution approaches Gaussian; decreasing α corresponds to increasingly non-Gaussian) and σ is a normalized vertical scale parameter analogous to the rms height of the sea surface. The example shown in Figure 3 demonstrates the improved capability of the α-s distribution for predicting the extreme observations in the tail of the distribution.

We have also used the α-s distribution function to model the one-dimensional profile of the sea surface. Corresponding backscatter predictions are then obtained using either the Kirchhoff Approximation (KA) or the Small Slope Approximation (SSA) of Voronovich [1994]. The appropriate choice of scattering model depends on the surface slope; the SSA is appropriate provided that the slopes of the rough surface are sufficiently small, whereas the KA applies under less restrictive conditions. Figure 4 illustrates a variety of sea surface roughness configurations obtained by varying the primary α-s model parameters, and also makes use of a third parameter, l, corresponding to the correlation length of the surface. Using the SSA and the KA, and assuming the experimental characteristics (e.g., viewing geometry, frequency, polarization) from the SAXON-FPN experiment, we obtained backscatter predictions based on s-α-s surfaces such as those shown in Figure 4. Preliminary validation of this approach has been obtained via comparisons between model predictions and observations of backscatter.

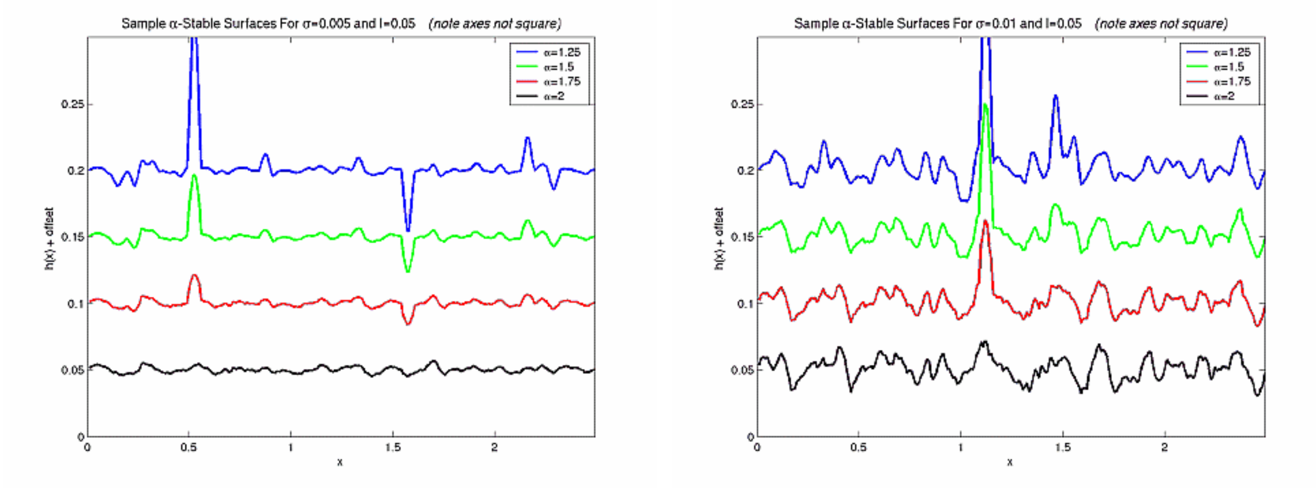

Figure 4. Illustration of surface roughness dependence on model parameters. For the surfaces depicted in the left panel, σ=0.005 and l=0.05; the dependence of the 'spikiness' of the surface on the parameter α is evident in the characteristics of the four traces in each panel. The trace at the bottom corresponds to α=2 (Gaussian) and deviation from Gaussianity increases vertically. The panel on the right has identical parameters as on the left, except the scale parameter σ=0.01.

IMPACT/APPLICATION

This project will lead to an improved understanding of the physical processes responsible for observed radar returns from the sea surface and will result in improved predictive capabilities for extreme backscattering events, for which the underlying processes are not well understood.

TRANSITIONS

The results of this project have not yet been transitioned for operational use.

RELATED PROJECTS

This project is directly related to NASA scatterometers, such as QuikScat, and are relevant to the study of sea surface scattering, particularly at high wind speeds.

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